STRUCTURAL BEHAVIOR UNDER PRECISION IMPACT TESTS

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INTRODUCTION AND BACKGROUND

One of the last frontiers in structural dynamics is the behavior of buildings under the effects of impact and explosions. Traditionally, this area has been under study by using field testing with high explosives (HE). In recent years, however, both the high cost and the well-known lack of precision associated with field HE tests are of great concern. Although valuable for many purposes, data from field tests may not be useful for precise description of complicated structural behavior or in support of development, verification and validation of numerical capabilities. The anticipated decline in funding for R&D in fortification science and technology is particularly critical when large scale tests are considered. Due to current limitations in numerical simulation capabilities, R&D organizations must rely on expensive tests to provide recommendations on specific problems. If the cost for obtaining such answers cannot be dramatically reduced, it could affect the viability of R&D in this critical field of science and technology. This paper examines a promising approach that shows significant potential to overcome this problem, and provides recommendations on how to implement it.

Similarly to requirements in other scientific areas, modern fortification technologies are founded on a combination of precision tests and sophisticated numerical simulations. The linkage between these two essential components has increased gradually over the last half century, and the driving force behind both the capabilities and requirements have been the rapid evolution in computer power. Nevertheless, because of current enhanced capabilities in both experimental and numerical analysis, the needs for stronger interaction and collaboration between researchers in these areas are greater than ever. This point of view has been emphasized in four related events. The Norwegian Defence Construction Service (NDCS) sponsored a three-day workshop (Krauthammer, June 1993) during which the invited participants discussed and evaluated the current knowledge and requirements for future research with respect to structural concrete slabs subjected to modern weapon effects. About three months later, the Defense Nuclear Agency (DNA) sponsored a two-day workshop devoted to verification and validation of nonlinear structural dynamics codes. Again, in October 1995, the Defense Nuclear Agency (DNA) sponsored a one day conference on verification and validation of nonlinear structural dynamics codes. Finally, the NDCS sponsored another three-day workshop (Krauthammer et al., May 1996) devoted to precision testing for computer code validation and verification. Although only very few individuals participated in all four events, the main conclusions and recommendations were essentially identical. It is clearly recognized that numerical simulations will play an increasingly more important role, eventually replacing many experimental studies. This shift is expected to translate into very significant cost reductions in future (most possibly before the end of this decade) fortification-related R&D. However, to enable this transition and to insure that it will be effective, it is required to concentrate in the near term on precision testing, as an integral part of development, verification and validation of the eventual numerical capabilities.

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Unfortunately, most R&D organizations active in the fortification area have not developed precision testing capabilities that could be used for the study of both small- and full-scale structural components. Such facilities are essential for obtaining test data that could be used to gain a deeper understanding of medium-structure interaction (MSI) and/or structural response to correlate the well defined and reproducible loads with carefully measured corresponding responses. This is not surprising, because most R&D organizations have been heavily involved in mission-oriented work. They have traditionally responded to their customers' needs, and did not have the time and resources to develop innovative technologies in anticipation of conditions that were likely to exist in the distant future. These conditions, however, were anticipated by a few individuals who embarked on a gradual and systematic development of innovative approaches that could be used effectively in support of computer code validation and verification.

Researchers have carefully considered various experimental approaches that could be adopted for this collaborative precision testing activity. Based on the available information, and following discussions during the NDCS-sponsored workshop on structural concrete slabs (Krauthammer, June 1993 and Krauthammer et al., June 1996), it has been suggested to explore impact testing approaches for achieving the stated objectives. The reasons for this selection are summarized next:

a. Impact testing is among the very few experimental techniques in short duration dynamics that insure a precise delivery of energy and impulse to a test article. This general approach has been used for many years also in material testing (for example, fracture toughness evaluation, split Hopkinson bar experiments, etc.). Clearly, identical amounts of energy and impulse can be insured in multiple tests. This is very difficult to achieve with other energetic testing methods. Therefore, this approach is definitely a "precision testing" approach.

b. Experimental data from impact testing can be used for code validation or verification. This is true for any type of load obtained in the test, even if the load has no direct relationship with a specific weapon effect. Nevertheless, one can achieve significant control on the important parameters that define a load function: Rise time, peak load, duration, and shapes of the loading and unloading branches of the function, as discussed below. Obtaining load functions that are generally similar to positive load phases obtained from typical weapons is possible, however, a direct relationship between such pulses has to be established and verified.

SOME ASPECTS OF IMPACT TESTING

The problem of impact between two bodies has been studied extensively (for example, Eibl 1987, Feyerabend 1988, Krauthammer 1989 and 1994, Thoma 1992, and Bischoff 1993). It has been shown that the impact problem can be formulated in light of Newton's Second Law of motion, as briefly outlined by Krauthammer during the First Cardington Conference (1994):

$$\mathbf{F} = M\ddot{\mathbf{u}} \qquad (1)$$

Now, consider a mass, M, impacting a structure with resistance, $\mathbf{R}(\mathbf{u})$, and derive the equation of dynamic equilibrium:

$$M\ddot{\mathbf{u}} - \mathbf{R}(\mathbf{u}) = 0 \qquad (2)$$

Yet, the structure also has a mass, and there is an impact resistance between the mass and the structure. The equation of equilibrium can be rewritten, as follows:

$$M_1\ddot{\mathbf{u}}_1 + \mathbf{R}_1 (\mathbf{u}_1 - \mathbf{u}_2) = 0 \qquad (3)$$

$$M_2\ddot{\mathbf{u}}_2 - \mathbf{R}_1 (\mathbf{u}_1 - \mathbf{u}_2) + \mathbf{R}_2 (\mathbf{u}_2) = 0 \qquad (4)$$

Where M_1, $\ddot{\mathbf{u}}_1$, $\mathbf{u}_1$ are the mass, acceleration and displacement of the impacting body (impactor), respectively. M_2, $\ddot{\mathbf{u}}_2$, $\mathbf{u}_2$ are the mass, acceleration and displacement of the impacted structure, respectively. $\mathbf{R}_1$ and $\mathbf{R}_2$ are the impact and structural resistance, respectively.

This system of equations describes the case of "Hard Impact" where the equations of dynamic equilibrium for the structure and impacting body are coupled. Typically the displacement of the impacting mass is much larger than the structural displacement (i.e., $\mathbf{u}_1 >> \mathbf{u}_2$), and therefore, Equation (3) can be rewritten as:

$$M_1\ddot{\mathbf{u}}_1 + \mathbf{R}_1 (\mathbf{u}_1) = 0 \qquad (5)$$

Equation (5) can be solved with Equation (1) to give:

$$\mathbf{R}_1(t) = \mathbf{F}(t) \qquad (6)$$

Now, Equation (4) can be rewritten as follows:

$$M_2\ddot{\mathbf{u}}_2 + \mathbf{R}_2 (\mathbf{u}_2) = \mathbf{R}_1 (\mathbf{u}_1) = \mathbf{F}(t) \qquad (7)$$

This case, where $\mathbf{u}_1 >> \mathbf{u}_2$, permits one to uncouple Equations (3) and (4), and it is defined as "soft impact". One can calculate the impact forcing function, $\mathbf{F}(t)$, from Equation (6) by assuming that the responding structure is rigid (i.e., $\mathbf{u}_2 = 0$), and then to compute the response of the deforming structure from Equation (7). Cases where explosive waves act on structures are close to the "soft impact" response, while cases where the displacements $\mathbf{u}_1$ and $\mathbf{u}_2$ are of the same order of magnitude do not allow the uncoupling of the Equations (3) and (4), and are close to the "hard impact" definition. One may also classify these two limiting phenomena in a more simplistic manner. In case of "soft impact" of a deformable mass on a rigid structure the kinetic energy of the impacting mass is transformed into plastic deformation of the impactor. However, with a "hard impact" the impactor's kinetic energy is transformed into deformation energy in both the impactor and the structure. In this second case, if the impactor is assumed to be rigid and is arrested by the structure, its kinetic energy is transformed into deformation energy in the structure. Penetration will dramatically complicate these cases, and one must resort to numerical evaluations.

This discussion illustrates how much control can be achieved by carefully selecting the corresponding parameters of the experimental setup. Nevertheless, it is important to show what types of load pulses

can be generated by impact testing, and their (qualitative) relationship with load pulses associated with HE detonations.

EXAMPLES OF IMPACT-INDUCED LOADS

Impact testing can provide a wide range of load pulses that can be used in a very controlled manner. To illustrate this important feature, several examples of experimental load pulses obtained from various impact devices are presented and discussed.

Yan (1992) studied the steel-concrete bond under impact loads and used a 345-kg drop hammer with low drop heights (some as low as 0.3 m). These studies represent a lower end of impact testing capabilities, since the corresponding velocities and the localized (i.e., load applied to a single bar) nature of the load resulted in lower peak forces and longer pulse durations. Indeed, the loading rates achieved in those tests ranged from $5*10^{-5}$ MPa/s to $5*10^{-3}$ MPa/s.

Other load-time histories were obtained from tests with a 2200-kg impactor on structural concrete bridge parapets using the large pendulum at Penn State. It should be noted that these data represent a very small range of loading pulses, since the drop height was only up to 0.91 m. This pendulum can be raised to about 13 m, the mass can be varied between less than 100 kg and 6,800 kg, and the bumper material and geometry can be varied from very soft to very hard. The use of special materials and shapes for the bumper will enable one to obtain a wide range of desired spatial pressure-time histories.

Thoma (1993) describes several impact testing devices and methods used successfully in Germany. These devices include both pendulum-type machines and drop hammers, whose general principals are similar to those discussed above. He showed two time histories from drop hammer impact tests (about 1100 kg at 13 m/s) on prototype and 1:8.5 model of a structural concrete T-beam. Good comparisons between the load pulses for both prototype and model were noted. The effect of impactor's head shape on the pulse shape was shown with flat and pointed drop hammer heads (about 1000 kg at 8.2 m/s) during tests on structural concrete slabs. Pointed heads result in a drastic reduction of the peak load, and a slight reduction in the duration. Thoma (1993) illustrated the effect of surface quality on the load pulse. It was found that an untreated concrete surface has a similar effect to that of a pointed impact head. He showed that the peak load was affected also by the concrete curing time (dryer concrete causes lower peak loads), concrete uniaxial strength (a 20% strength increase caused a 30% increase in the peak load), and by the size of the specimen (smaller sizes cause higher peak loads).

All these load pulses show a relationship between the impact conditions and the pulse shape. Low velocity impact will result in a smooth, long, almost half-sine waves, load pulses. As the impact velocity increases, the rise time shortens, the peak pulse increases, a main initial pulse with shorter duration emerges, and subsequent secondary pulses become less important.

Data collected during calibration tests for the drop hammer at PSU show the ability to obtain a wide range of load functions. The 26.75 kN (6000 lbs) hammer was dropped from different heights on a

segment of steel rail attached to a prestressed concrete railway tie, and the impact interface and support conditions were varied. The load pulses were measured with a steel load cell attached to the impacting face of the hammer. Two accelerometers were mounted on the top surface of the railway tie: No. 1 at 250 mm and No. 2 at 1000 mm from the center of the steel rail, respectively. Although several tests were performed, the data for two cases can be used to illustrate the potential of this testing system. One load pulse was obtained for a drop height of 150 mm, the concrete tie was simply supported on 25 mm rubber pads and another 25-mm rubber pad was placed between the hammer and the steel rail. The peak load of about 193 kN was reached at 38 ms after impact (3.76 kN/ms), and the pulse shape is quite smooth and triangular. The second load pulse was obtained for a drop height of 300 mm. The rubber pads were removed from the steel supports and from the interface between the hammer and the rail. Here, several local peak loads were observed. The first, 188 kN at 1.35 ms after impact (139 kN/ms), while the third was about 276 kN at 7.5 ms after impact (36.8 kN/ms).

Under the first load pulse, the peak accelerations were about 13 g and 8 g for accelerometers 1 and 2, respectively. Higher frequency signals appeared at 120 ms were caused by the load cell slipping off the rubber pad and hitting the steel rail, and it highlights the differences between different types of impact. For the second load pulse, the peak accelerations were about 300 g and 200 g for accelerometers 1 and 2, respectively.

In the frequency domain, for the first load pulse, both accelerometers exhibited power spectra in the range between zero and about 100 Hz. However, that for accelerometer 1 had a peak of about 0.13 at 15 Hz while accelerometer 2 showed two peaks of about 0.038 at both 15 and 100 Hz. For the second load pulse, one could notice a significant difference between the two signals. Accelerometer 1 had a power spectrum range between zero and 1700 Hz, with the major peak of about 0.38 at 25 Hz, and several gradually lower peaks in the range of up to 500 Hz. Accelerometer 2 had a power spectrum between zero and about 650 Hz. It showed four distinct peaks in the range less than 100 Hz (the highest of about 0.28 at 75 Hz) and then three lower peaks at 120 Hz, 200 Hz and 570 Hz.

Clearly, one can study in great detail the characteristics of both the applied load and the structural response, thus, deriving well-defined relationships between cause and effect. Such data would be very valuable for the validation and verification of computer codes, since the analysts could determine if, and how accurately, they could capture the same physical phenomena observed during the tests. Furthermore, from the physical data, numerical analysts could assess the reasons for deviations between numerical and test data, and introduce modifications to remedy the problem.

Noting that this hammer can be dropped from a maximum height of 7 m is important, and the data shown above is at the very low end of anticipated loading pulses. Thus, one should expect a very broad range of physical data that will enable the validation and verification of computer codes over a wide range of both time and frequency domains.

For all the cases discussed above, the rise time varied from about 3.76 kN/ms to 23,000 kN/ms. Obviously, using higher velocity devices is expected to provide even steeper load pulses. The selection of interface material (type and thickness) is expected to affect the load pulse, but this needs to be evaluated further.

As for the negative loading phase, it has been shown that the effect of the negative loading phase from conventional explosives could be significant on lightweight structural elements (Altenberg and Krauthammer, 1996). However, based on the discussions during the NDCS-sponsored workshop in 1993, it is unlikely to be very significant when heavy structural concrete systems are considered under the same type of environments. Therefore, it is expected that the proposed precision tests should provide meaningful data in support of code validation and verification.

REPRODUCIBILITY OF TEST RESULTS

Addressing the issue of reproducibility is important, since it is one important reason for initiating this research effort. Supporting information is found in the references cited above. Obviously, assuming a well maintained testing facility, one has excellent control on the potential energy levels that propel the impact device toward test articles. Nevertheless, careful attention must be given to specimen preparation to insure comparable load pulses, as shown by Thoma (1992), and briefly mentioned above. Under such conditions, one should expect little variation (less than 10%) on the peak load values. Based on the supporting information from other impact testing facilities, the reproducibility of such tests is assessed as very good. Repeated testing (at least three tests per specimen to insure load pulse stability), and cross correlation between testing organizations will insure data objectivity.

PRECISION IMPACT TESTING FACILITIES AT PENN STATE

Structural testing under short duration dynamic loads can be performed on several devices at or associated with the laboratory. A large outdoor impact pendulum facility consists of a 15.25 m high steel frame capable of swinging weights of up to 67 kN through an arc with a vertical drop height of up to 13 m. Additional advanced impact testing devices have been recently added with support from the National Science Foundation and the University. An indoor impact pendulum facility consisting of a 4.25 m high steel frame. It is capable of swinging weights of up to 7.1 kN through an arc with a vertical drop height of about 3.65 m, and a 8.9 m 26.75 kN drop hammer device with a 7 m drop height. These devices are expected to be modified over time further to enhance their capabilities. Several multi-channel high-speed (up to 1 mega samples per second) data acquisition systems supports these testing devices.

Additional high precision testing devices for short duration dynamics include an Instron 1331 dynamic testing machine. The actuator can deliver a maximum force of 19.62 kN with a maximum stroke of +/- 165 mm. The dynamic testing rate for the closed loop system is up to 17 m/s (Actually, a velocity of more than 23 m/s was obtained, and the device can be operated also in an open loop mode at faster loading rates). As far as data acquisition, these systems are supported by various very high speed data collection systems (up to 1 MHZ) for strain, displacement, force, etc., including a 12,000 frames per second SP2000 camera and a copper vapor laser system (a one million frames per second camera in the College of Engineering can be used also if required).

CONCLUSIONS AND RECOMMENDATIONS

There is a serious lack of knowledge on how such facilities (office buildings, schools, hospitals, power stations, etc.) behave under blast and shock loads. Many materials and components were never studied for such applications, and most nations do not have the required resources to approach this problem in the "old-fashioned way". Future R&D in this area must rely heavily on the development of precision testing methods aimed at supporting computer code validation and verification. Furthermore, a strong multinational effort is urgently needed to address this challenge, and to insure that sponsoring organizations will be both guided and educated to move in this direction. The collaborative R&D activities will insure that the parallel work will be well coordinated, and that the resources will be efficiently used. Furthermore, cross-checking and mutual assessments of methods and data will insure that the maximum amount of knowledge will be extracted from such data, and be wisely carried out to protect the public against serious consequences.

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